ESC-TR-95-053

Project Report
RASSP-4

I/Q Baseband Demodulation in the RASSP SAR Benchmark

DTIC
S ELECTE D
SEP 2 6 1995
G

G.A. Shaw
S.C. Pohlig

24 August 1995

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

Prepared for the Advanced Research Projects Agency
under Air Force Contract F19628-95-C-0002.

Approved for public release; distribution is unlimited.

19950925 007

This report is based on studies performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology. The work was sponsored by the Advanced Research Projects Agency under Air Force Contract F19628-95-C-0002.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Gary Tutungian

Gary Tutungian
Administrative Contracting Officer
Contracted Support Management

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

I/Q BASEBAND DEMODULATION IN THE RASSP SAR BENCHMARK

G.A. SHAW
S.C. POHLIG
Group 97

Accesion For		
NTIS CRA&I ☒		
DTIC TAB ☐		
Unannounced ☐		
Justification		
By		
Distribution /		
Availability Codes		
Dist	Avail and / or Special	
A-1		

PROJECT REPORT RASSP-4

24 AUGUST 1995

Approved for public release; distribution is unlimited.

LEXINGTON MASSACHUSETTS

ABSTRACT

This technical note describes the theory of digital in-phase and quadrature (I/Q) demodulation as it is applied in the baseband demodulation of synthetic aperture radar data for the Advanced Detection Technology Sensor (ADTS) operated by MIT Lincoln Laboratory. The ADTS SAR data, and the associated demodulation and image formation algorithms, constitute the application thread for the first two benchmarks in the ARPA program for Rapid Prototyping of Application Specific Signal Processors (RASSP). In this note, the I/Q filter response in the baseline ADTS algorithms is examined, and two alternative filter designs are presented.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. DIGITAL DEMODULATION OF ADTS DATA

1.1 Introduction

The in-phase and quadrature demodulation required for the SAR benchmark application is succinctly described in Section 2.1.3 of Benchmark Technical Description-1 (BTD-1)[1]. A set of 16 baseline filter coefficients are provided in Table 3 of BTD-1, and a requirement to accommodate up to 96 coefficients is imposed. However, BTD-1 does not provide any explanation of the theory on which the I/Q demodulation is based, nor does it provide a set of 96 filter coefficients.

This note reviews the I/Q demodulation theory and provides two additional sets of filter coefficients. With the information provided in this note, any technique for designing FIR low-pass filters can be applied to obtain a replacement I/Q filter of any desired length.

The general topic of digital I/Q demodulation utilizing Hilbert transforms (analytic filters) is covered in a number of papers and books, for example [2]-[4]. The description presented here is specialized to the implementation chosen in the baseline ADTS algorithms.

1.2 Quadrature Signal Representation

It is convenient and computationally attractive to represent real-valued bandpass signals, such as commonly encountered in radar, using an equivalent complex low-pass (in-phase and quadrature) representation. The rationale for I/Q representation is further described in [5]. Prior to the advent of high-speed A/D converters, I/Q demodulation for high-bandwidth waveforms was usually accomplished in the analog domain by a system similar to the one portrayed in block diagram form in Figure 1.

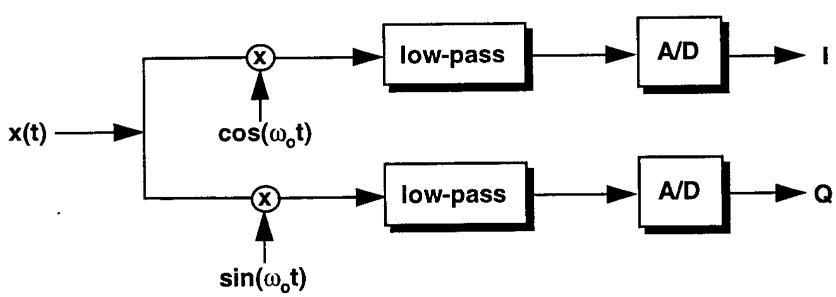

Figure 1. Analog I/Q demodulation followed by A/D conversion.

1.3 ADTS Sampled Spectrum

In the ADTS system, stretch processing[1] is used to convert the 600 MHz bandwidth waveform at RF down to a 50 MHz bandwidth waveform centered at a low IF frequency of 31.25 MHz. This real signal is then sampled at 125 MHz. Abstracting these numbers, the sampling frequency may be denoted by F_s, the signal bandwidth is then $.4F_s$, and the signal spectrum is centered at $.25F_s$, as illustrated in Figure 2a.

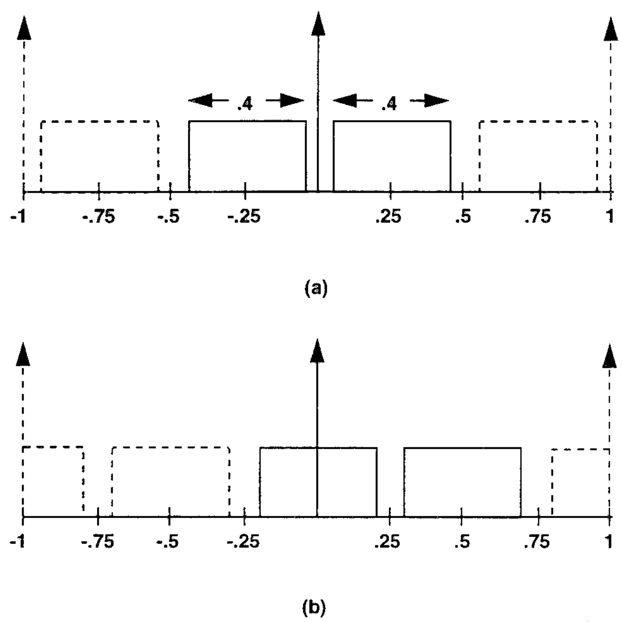

Figure 2. (a) Sampled bandpass signal spectrum (b) Spectrum shifted to baseband.

1.4 Digital I/Q Demodulation

The in-phase and quadrature baseband representation of a bandpass signal like that of Figure 2a can be obtained by suppressing the positive frequency component of the real spectrum and translating the negative frequency component to baseband. Since the positive frequency components are suppressed, the sampling rate can be subsequently reduced by a factor of $2\times$ without incurring any aliasing[1]. The implementation of these operations in the baseline ADTS algorithms is based on the following sequence of operations:

1. Shift the real spectrum by $.25F_s$ so the spectral images are centered at 0 and $.5F_s$ as shown in Figure 2b.
2. Pass the shifted signal through a low-pass filter with a nominal cutoff in the range $.20F_s < f_c < .25F_s$ and a stop band centered at $.5F_s$.
3. Discard every other complex output sample produced by the filter to achieve a sample rate reduction of 2.

The input signal spectrum can be shifted by $.25F_s$ by multiplying the input signal by $\exp(\jmath 2\pi F_s n\Delta t/4)$, where $\Delta t = 1/F_s$, which is equivalent to multiplying the digital sequence by $\jmath^n$. The block diagram of a system for implementing these operations is shown in Figure 3, where the decimation in sampling frequency is achieved by discarding odd output samples.

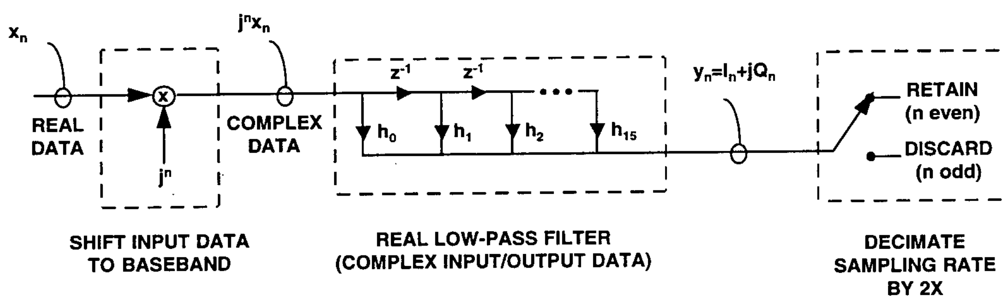

Figure 3. Digital I/Q demodulation with decimation.

Since only the even complex samples are retained from the filter, it is possible to reduce the computational burden by computing only the samples which are to be retained. Table 1 contains the convolution sequence representing the first few even and odd output samples, denoted by y_n. Note that in the retained (even) output samples, the even samples of the modulated input sequence, which are real, are always associated with the even coefficients in the lowpass filter, while the odd samples of the modulated input sequence, which are imaginary, are always associated with the

[1]In actuality, the frequencies in the stopband of the filter will alias but are assumed to be sufficiently attenuated to permit the sample rate reduction.

odd coefficients in the lowpass filter[2]. Therefore, the lowpass filter can be split into even and odd coefficient "8-tap" filters, each of which operates on only the even or odd components of the input signal respectively to produce the real and imaginary output samples *after* decimation. The system of Figure 3, can be rearranged as shown in Figure 4, which is the form described in Section 2.1.3 of BTD-1.

TABLE 1

Sequence of I/Q Filter Output Samples

Retain	Discard	n	Output, $y_n = \sum_{k=0}^{15} h_k \jmath^{n-k} x_{n-k}$
$\surd$		0	$h_0(x_0)$
	$\surd$	1	$h_0(\jmath x_1) + h_1(x_0)$
$\surd$		2	$h_0(-x_2) + h_1(\jmath x_1) + h_2(x_0)$
	$\surd$	3	$h_0(-\jmath x_3) + h_1(-x_2) + h_2(\jmath x_1) + h_3(x_0)$
$\surd$		4	$h_0(x_4) + h_1(-\jmath x_3) + h_2(-x_2) + h_3(\jmath x_1) + h_4(x_0)$

1.5 Baseline I/Q Filter

The baseline I/Q filter coefficients given in BTD-1 are repeated in Table 2. The even and odd coefficients represent a 16-tap low-pass filter with the magnitude response shown in Figure 5. The equivalent I/Q filter after frequency shifting is shown in Figure 6.

The low-pass filter has a DC gain of 2.3 (7.23 dB), and provides 36 dB of rejection relative to the passband. The filter therefore suppresses the positive frequency spectrum of the bandpass signal by 36 dB relative to the retained negative frequency spectrum. However, the suppressed spectrum is still coherent and will experience the same integration gain as the unsuppressed spectrum during range compression, with the result that artifacts from the positive frequency spectrum will be aliased into the range-compressed pulse 36 dB below the desired returns at the complementary range. These artifacts are not readily visible in a processed image since the eye can only discern

[2]For simplicity, the even ouput sequences starting with $n = 0$ are shown as retained. In practice, the first 16 samples (8 even-odd sample pairs) serve only to initialize the filter, and output samples are not retained before $n = 16$.

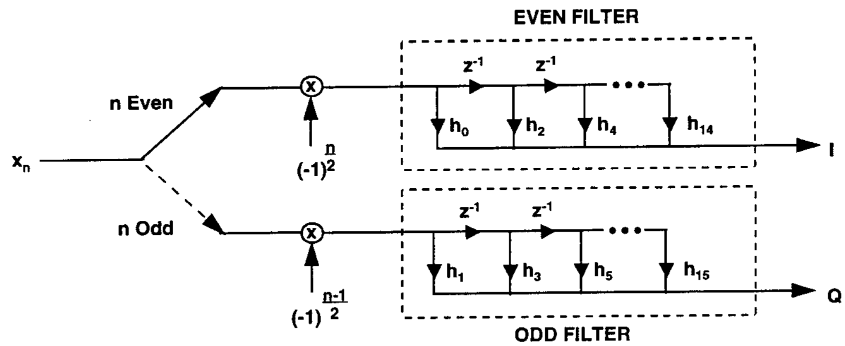

Figure 4. Baseline digital I/Q demodulation system.

TABLE 2

Baseline I/Q Filter Coefficients

Index	Even	Odd
0	-.021133	.019827
1	.055895	-.011912
2	-.148449	-.067483
3	.406139	.917516
4	.917516	.406139
5	-.067483	-.148449
6	-.011912	.055895
7	.019827	-.021133

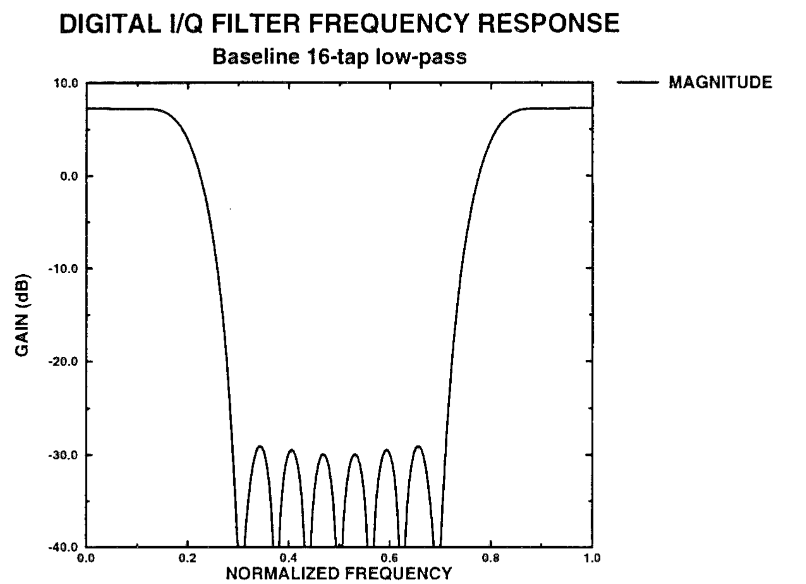

Figure 5. Baseline low-pass filter with 16 coefficients.

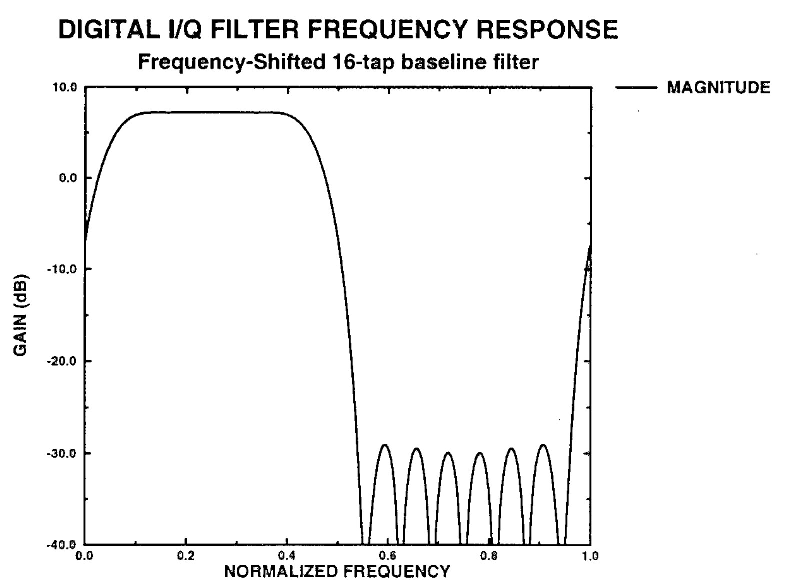

Figure 6. Frequency-shifted baseline low-pass filter.

about 6 to 8 bits of dynamic range in an image, with each bit corresponding to 6 dB. Therefore, 36 dB of suppression corresponds to about 6 bits of dynamic range and the artifacts are not visually perceptible in a 8-bit image display.

Although the artifacts are not visually observable, they may affect subsequent processing for detection or target recognition. Increasing the stopband rejection in the I/Q filter will help to reduce the impact of image artifacts associated with large amplitude scatterers. The next chapter provides two alternative filter designs, both with better stopband rejection and one with substantially narrower transition bands.

2. IMPROVED I/Q FILTER DESIGNS

2.1 Improved Rejection with 16 Taps

Table 3 lists the coefficients for a 16-tap filter with improved stopband rejection. The filter was designed by a applying a Dolph-Chebyshev window with -50 dB sidelobes to a sinc function. A fractional bandwidth of .43 was specified, corresponding to a nominal cutoff of $.215F_s$ for the low-pass filter. The magnitude response of the corresponding low-pass filter is shown in Figure 7. Note that stopband rejection in excess of 60 dB is achieved with the same number of taps used in the baseline filter.

TABLE 3

Improved I/Q Filter Coefficients

Index	Even	Odd
0	-0.00319687	0.00840285
1	0.0299313	-0.0135345
2	-0.125032	-0.0534323
3	0.407175	0.925679
4	0.925679	0.407175
5	-0.0534323	-0.125032
6	-0.0135345	0.0299313
7	0.00840285	-0.00319687

Visual images produced with the improved 16 tap filter are not easily differentiated from images produced with the baseline filter, but a histogram of the two images shows readily discernible differences in the distribution of pixel amplitudes.

2.2 Improved Transition Band and Rejection with 96 Taps

Table 4 lists the coefficients for a 96-tap filter with improved transition bands and stopband rejection. The filter was again designed by applying a Dolph-Chebyshev window to a sinc function. In this case, -60 dB sidelobes were specified for the window and a fractional bandwidth of .43 was again specified. The fact that the FIR filter is six times longer than the baseline filter accounts for the improved transition bands as shown in the magnitude response of Figure 8. However, the filter requires six times more range samples than the baseline filter for initialization. The stopband

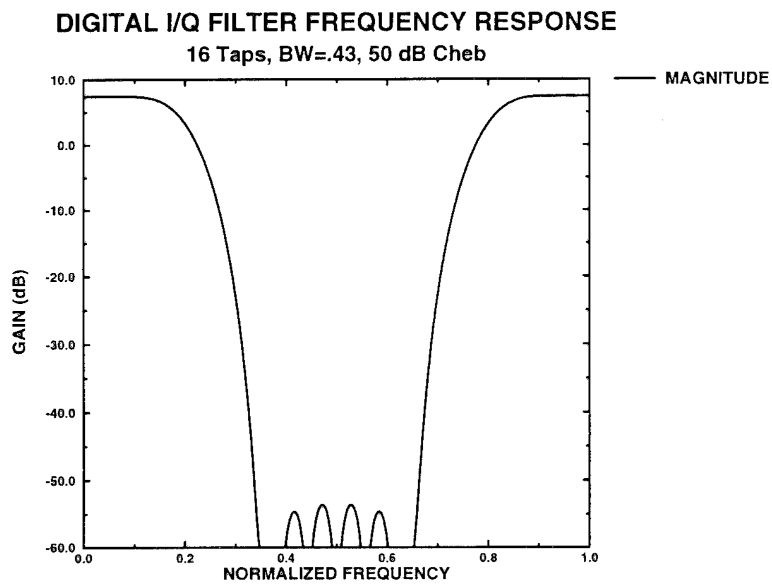

Figure 7. *Low-pass filter with 16 coefficients and improved stop-band rejection.*

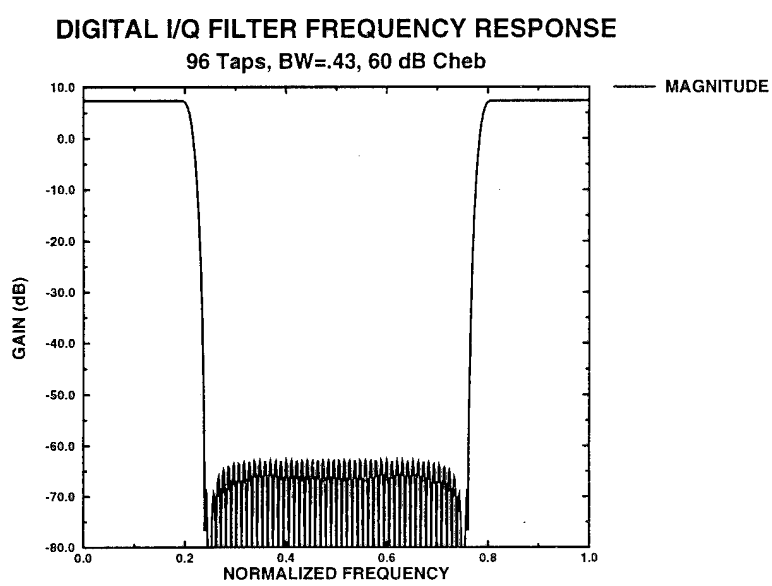

Figure 8. *Low pass filter with 96 coefficients.*

rejection is approximately 70 dB below the passband, and could be made even lower at the expense of wider transition bands.

Visually, effects of the 96 tap filter on the SAR images are most evident at the near and far ranges, where the sharp transition band of the filter results in a much quicker drop off in amplitude at the upper and lower image boundary.

2.3 Comments

The additional filters presented in this note were designed using a simple windowing method, and the choice of a Dolph-Chebyshev window results in ripples in both the passband and the stopband. Other design methods are available which maximize passband flatness or allow the amount of passband and stopband ripple to be traded-off against one another. Any filter design technique can be applied to obtain an I/Q filter for the SAR processor, provided the appropriate passband and stopband regions are preserved, and the filter is implemented in accordance with Figure 4.

TABLE 4

Coefficients for 96 Tap I/Q Filter

Index	Even	Odd
0	0.000468169	-4.67811e-06
1	-0.000385445	-0.000209461
2	0.000517049	0.000615271
3	-0.000467803	-0.00117829
4	6.96315e-05	0.00174678
5	0.000807673	-0.00204086
6	-0.00216669	0.00169454
7	0.00379613	-0.000360091
8	-0.00522678	-0.0021377
9	0.00576788	0.0056349
10	-0.00464648	-0.00950648
11	0.0012425	0.0126507
12	0.00462394	-0.0136249
13	-0.0124277	0.0109419
14	0.0207838	-0.00348745
15	-0.0274776	-0.00902558
16	0.0297083	0.0256746
17	-0.0245096	-0.0441112
18	0.00922689	0.0605374
19	0.0181721	-0.0697347
20	-0.0593722	0.0645643
21	0.117744	-0.0324609
22	-0.208044	-0.0685609
23	0.441974	0.925679
24	0.925679	0.441974
25	-0.0685609	-0.208044
26	-0.0324609	0.117744
27	0.0645643	-0.0593722
28	-0.0697347	0.0181721
29	0.0605374	0.00922689
30	-0.0441112	-0.0245096
31	0.0256746	0.0297083
32	-0.00902558	-0.0274776
33	-0.00348745	0.0207838
34	0.0109419	-0.0124277
35	-0.0136249	0.00462394
36	0.0126507	0.0012425
37	-0.00950648	-0.00464648
38	0.0056349	0.00576788
39	-0.0021377	-0.00522678
40	-0.000360091	0.00379613
41	0.00169454	-0.00216669
42	-0.00204086	0.000807673
43	0.00174678	6.96315e-05
44	-0.00117829	-0.000467803
45	0.000615271	0.000517049
46	-0.000209461	-0.000385445
47	-4.67811e-06	0.000468169

GLOSSARY

A/D	Analog to Digital
ADTS	Advanced Detection Technology Sensor
BTD	Benchmark Technical Description
FIR	Finite Impulse Response
IF	Intermediate Frequency
I/Q	In-Phase and Quadrature
MHz	Megahertz
RASSP	Rapid Prototyping of Application Specific Signal Processors
RF	Radio Frequency
SAR	Synthetic Aperture Radar

REFERENCES

1. B. W. Zuerndorfer, et al. "RASSP benchmark-1 technical description," *MIT Lincoln Laboratory Project Report RASSP-1,* 25 Jan. 1995.

2. D. W. Rice, "Quadrature sampling with high dynamic range," *IEEE transactions on Aerospace and Electronic Systems,* Nov. 1982, pp 736-739.

3. A. V. Oppenheim and R. W. Schafer, *Digital Signal Processing,*, Prentice Hall, 1975.

4. L. R. Rabiner and B. Gold, *Theory and Application of Digital Signal Processing,* Prentice Hall, 1975.

5. E. Bedrosian, "The analytic signal representation of modulated waveforms," *Proceedings of the IRE,* Oct. 1962.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	24 August 1995	Project Report

4. TITLE AND SUBTITLE

I/Q Baseband Demodulation in the RASSP SAR Benchmark

5. FUNDING NUMBERS

C — F19628-95-C-0002
PE — 63739E
PR — 394

6. AUTHOR(S)

Gary A. Shaw and Stephen C. Pohlig

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Lincoln Laboratory, MIT
244 Wood Street
Lexington, MA 02173-9108

8. PERFORMING ORGANIZATION REPORT NUMBER

PR-RASSP-4

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

ARPA/ESTO
3701 N. Fairfax Dr.
Arlington, VA 22203

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

ESC-TR-95-053

11. SUPPLEMENTARY NOTES

None

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

This technical note describes the theory of digital in-phase and quadrature (I/Q) demodulation as it is applied in the baseband demodulation of synthetic aperture radar (SAR) data for the Advanced Detection Technology Sensor (ADTS) operated by MIT Lincoln Laboratory. The ADTS SAR data and the associated demodulation and image formation algorithms constitute the application thread for the first two benchmarks in the ARPA program for Rapid Prototyping of Application Specific Signal Processors (RASSP). In this note, the I/Q filter response in the baseline ADTS algorithms is examined, and two alternative filter designs are presented.

14. SUBJECT TERMS

design automation	RASSP	rapid prototyping	digital design
synthetic aperture radar	process metrics	parametric cost estimation	digital signal processing
benchmark	VHDL	virtual prototype	

15. NUMBER OF PAGES

28

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Same as Report